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A Numerical Simulation Study on Ocean Wave Effect and the Sensitivity of a Regional Atmosphere-Ocean Coupled Model

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Abstract

The ocean wave effect on the air-sea interaction is studied by numerical simulation tests and the sensitivity of a regional atmosphere-ocean coupled model to sea surface roughness parameterizations is also discussed in this paper. The results show that ocean waves influence the sea surface roughness. By considering the dependent relationship between sea surface roughness and wave age, the effect of ocean waves on air-sea interaction under high wind condition is significant and can not be ignored. The regional atmosphere-ocean coupled model shows good capability in simulating the typhoon processes which improves the simulation results of typhoon track and intensity. The coupled model is sensitive to sea surface roughness parameterizations. In these tests, the coupled model using the parameterizations of Smith and Liu gave better results. This study is helpful to make more reasonable parameterizations of the physical process of air-sea interaction and improve the regional atmosphere-ocean coupled models.

Keywords: air-sea interaction, sea surface roughness, wave age, atmosphere-ocean coupled model, typhoon.

1. Introduction

The interaction between the two important kinds of geophysical fluid, air and sea, is a hot topic in geophysical study. The exchange of heat, moisture and momentum between air and sea has long been recognized as a fundamental process in the development of mesoscale atmospheric phenomena such as tropical cyclones, boundary layer jets, and precipitating systems [1]. This air-sea exchange takes place at air–sea interface in the wave boundary layer, which implies that oceanic surface waves are of a potential impact on the air-sea interaction process.

The atmosphere-ocean coupled model is an important tool to study air-sea interaction. It has been widely used in the simulation study of large-scale weather prediction and climate change. In the

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mesoscale and small-scale weather process, however, the impact of air-sea interaction is more significant. The coupled model also provides an effective way in the relevant studies. Under high wind conditions, the development and breaking of ocean surface waves play a very important role in the process of air-sea interaction. Therefore the effect of ocean waves should be included in the coupled model. In this paper, a regional atmosphere-ocean coupled model with the effect of ocean waves is studied by numerical simulation tests of typhoon. The sensitivity of the coupled model to sea surface roughness parameterizations is also discussed in the tests.

2. Research Of Sea Surface Roughness Parameterization Schemes

Ocean waves take part in the exchange of momentum, heat and material at air-sea interface directly. The impact of ocean waves on the synoptic systems over the sea is mainly caused by the variation of sea surface roughness, which is important in calculating sea surface flux and chosen as the factor of the coupling model.

A typical parameterization of sea surface roughness used in most mesoscale atmospheric model is defined by Charnock in 1955 [2]:

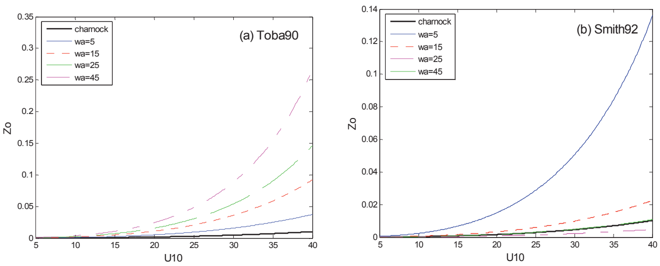
$$z_0 = \beta u_*^2 / g \tag{1}$$

In (1) z_0 denotes sea surface roughness, u_* denotes friction velocity and β is Charnock constant. However, many results of experiments and observations show that sea surface roughness is not only relevant to the sea surface wind but also dependents on ocean wave states. Based on the similarity of wave spectrum, Stewart (1974) [3] proposed an extension of the Charnock relation, in which the Charnock constant was defined as a function of wave age (2), where c_p denotes the wave phase speed and c_p / u_* is wave age parameterization. Based on this formula, researchers draw up some functions of β using experiment results or observations on the sea.

$$\beta = f(c_p / u_*) \tag{2}$$

Toba et al.（1990）[4] analyzed the experiment results combining with observations and eliminated the influence of ground swell, then he pointed out that Charnock parameterization increased with the increasing of wave age. But Smith (1992) [5] held the opposite opinion by analyzing HEXOS data. He discovered that Charnock parameterization decreased when wave age increased. Referring to the relationship between Charnock parameterization and wave age, researchers also hold some different opinions. In 2001, the SCOR 101 group analyzed a large number of data synthetically and the results showed that Charnock parameterization did not simply increase or decrease with changed wave age [6]. According to the result, they developed a new scheme to parameterize sea surface roughness.

The three parameterization schemes are based on observations under low wind condition. Because of the influence of sea spray and breaking up of ocean waves, the relationship between Charnock parameterization and wave age is more complex under high wind. Liu, B. and C. Guan (2007) [9] advanced a new parameterization scheme that includes the influence of sea spray and adapts to both high and low wind conditions. The four parameterizations of sea surface roughness above (Toba90, Smith92, SCOR01 and Liu07 are for short) are discussed in the coupled model. Figure 1 shows the difference of the four parameterizations and the contrast to the typical parameterization defined by Charnock. Then the research and results of sea surface roughness parameterization schemes are listed in Table 1.



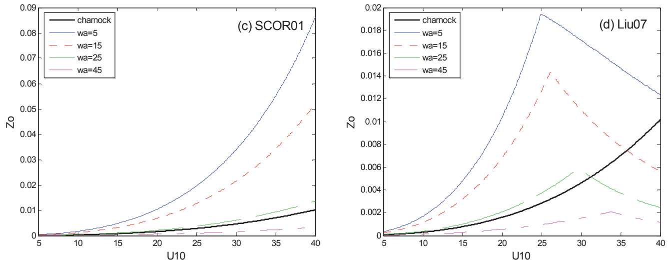


Fig.1 Variations of sea surface roughness at different wave age
(a) Toba90, (b) Smith92, (c) SCOR01, (d) Liu07

Table 1 Summarizations of sea surface roughness parameterization schemes

Authors	Sea surface roughness parameterization	
Toba and Koga (1986)	$z_0 = \beta u_*^2 / g$ $\beta = n(c_p / u_*)^m$	n=0.025, m=1.0
Toba et al. (1990)		n=0.02, m=0.5
Maat et al. (1991)		n=0.8, m= -1.0
Smith et al. (1992)		n=0.48, m= -1
Vickers and Marht (1997)		n=2.9, m= -2.0
Johnson et al. (1998)		n=1.89, m= -1.59
Drennan et al. (2003)		n=1.7, m= -1.7
Jones and Toba (2001)	$z_0 = \beta u_*^2 / g$ $\beta = \begin{cases} 0.03(c_p/u_*)\exp(-0.14c_p/u_*) & 0.35 < c_p/u_* < 35 \\ 0.008 & c_p/u_* \ge 35 \end{cases}$	
Taylor and Yelland （2001)[7]	$z_0 / h_s = 1200(h_s / l_p)^{4.5}$ h_s denotes significant wave height, l_p denotes wave steep	
Makin et al. （2005)[8]	$z_0 = c_l^{1-1/\omega}\beta^{1/\omega}u_*^2 / g$ $c_l = 10$ ， $\omega = min(1, \alpha_{cr} / \kappa u_*)$ $\alpha_{cr} = 0.64 m/s$	
Liu,B. and C.Guan (2007)	$\frac{g z_0}{u_*^2} = \begin{cases} (0.085\alpha_*^{3/2})^{1-1/\omega}[0.03\alpha_*\exp(-0.14\alpha_*)]^{1/\omega} & 0.35 < \alpha_* < 35 \\ 17.60^{1-1/\omega}(0.008)^{1/\omega} & \alpha_* \ge 35 \end{cases}$ $\alpha_* = c_p / u_*$ $\omega = min(1, \alpha_{cr} / \kappa u_*)$ $\alpha_{cr} = 0.64 m/s$	

3. Regional Atmosphere-Ocean Coupled Model Description

In this paper, a regional atmosphere-ocean coupling model is formed which consists of the mesoscale atmospheric model MM5, the regional marine model POM and the third-generation ocean wave model WW3. It includes both the dynamical and thermal interaction processes at air-sea interface [10].

Under high wind condition, such as typhoon, there are large exchange of momentum, heat, and water vapor between the atmosphere and the oceans, which leads to the strong response of the upper ocean. The strong wind stress on the sea surface makes rapid evaporation and cools the sea surface, at the same time, it thickens the mixed layer and warms the ocean sub-surface by putting warmer water into it. Furthermore, the ocean current in mixing layer is also strengthened. The heat flux from ocean to atmosphere enhances or maintains the movement of atmospheric system. Based on the analyses above, in the coupled model, MM5 provides surface heat flux to POM as its upper boundary conditions and the sea surface temperature calculated in POM is inputted into the atmospheric model MM5.

In the coupled model, MM5 provided the sea surface wind to drive the ocean wave model WW3, and the wave age parameter calculated in WW3 was inputted into MM5. Then the four sea surface roughness parameterization schemes is used in MM5.

The current-wave interaction was also considered in the coupling model. Sea surface current was transferred from POM to WW3 and the wind stress including the influence of ocean waves was inputted into POM through MM5. As described above, the three models were coupled one another and information communications are back and forth among the three (Fig. 2).

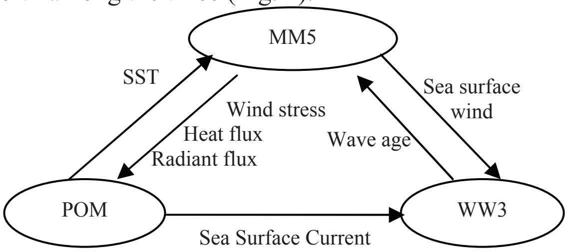


Fig.2 Schematic diagram of the model coupling

4. Experiments and results

4.1. Case selection

In order to test the sensitivity of the coupled model to sea surface roughness parameterizations, two different kinds of tropical cyclones are selected in the case studies. The typhoon ‘Chanchu’ (0601) was generated on the western Pacific and then went west into the South China Sea. In the process of moving, it changed its direction to the north suddenly and landed soon. Therefore, it is a typical turnaround typhoon. The typhoon ‘Prapiroon’ (0606) was generated in the South China Sea and classified as a straight forward typhoon.

4.2. Experiment design

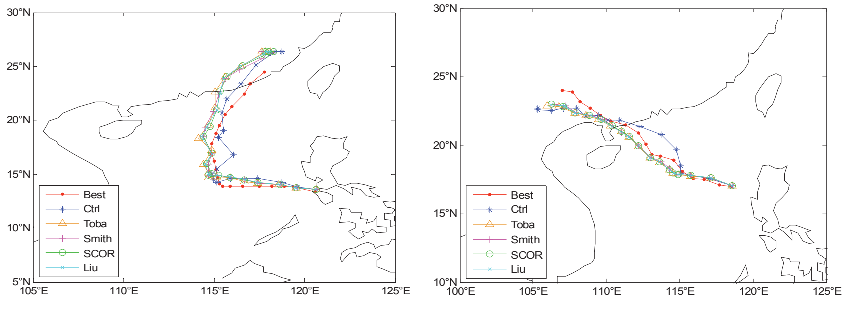
Five experiments are designed to simulate the two processes of typhoon using the coupled model (Tab.2). In the test of ‘Chanchu’ the integration period is from 0000UTC 13 May to 0000UTC 18 May 2006. In the test of ‘Prapiroon’ the integration period is from 0000UTC 1 August to 0000UTC 5 August 2006.

Table 2 Experiment design for typhoon ‘Chanchu’ and ‘Prapiroon’

Name	Content and techniques	Character
Ctrl	Uncoupled atmospheric model (MM5). sea surface roughness parameterization scheme by Charnock.	Control run
Toba	Coupled model. sea surface roughness parameterization scheme of ‘Toba90’.	Sensitivity run
Smith	Coupled model. sea surface roughness parameterization scheme of ‘Smith92’.	
SCOR	Coupled model. sea surface roughness parameterization scheme of ‘SCOR01’.	
Liu	Coupled model. sea surface roughness parameterization scheme of ‘Liu07’.	

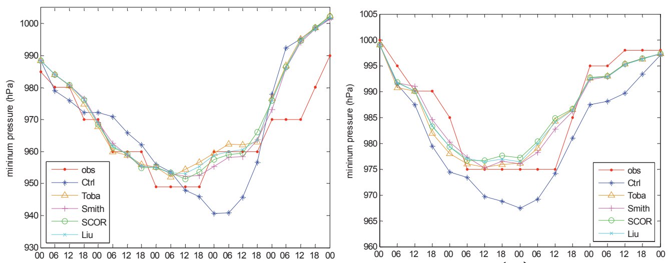
4.3. Experiment results

Figure3 shows the simulated track of typhoon in control and sensitivity runs. Compared with control run, the results of coupling run are closer to the best track. The difference between sensitivity runs is small. Therefore the coupled model is not sensitivity to sea surface roughness parameterization schemes in simulating typhoon tracks. Figure 4 shows the variations of minimum sea level pressure of ‘Chanchu’ (a) and ‘Prapiroon’ (b) in the tests. The coupled model, with air-sea interaction, has significantly improved the simulation results of the intensity of typhoons. Compared with the control run, the simulated intensity of typhoon of coupled model is weakened influenced by air - sea interaction, which is closer to the observations. The coupled model is sensitivity to sea surface roughness parameterization schemes in studying the intensity of typhoon. In the four sensitivity runs, the directions of wave effect are the same but grades of the effect are different. When the typhoon system is developing, the effect of ocean waves is more significant and the difference between the simulated results of coupled model with different sea surface roughness parameterizations is much more notable. Comparing the four groups of simulation results , the sea surface roughness parameterization ‘Toba90’ has greatest impact on the evolution of typhoon system, but in the tests of the two typhoon processes in this paper, Compared with observations, the coupled model using the parameterizations of Smith92 and Liu07 give better results compared to the observations. Table 3 lists the statistics of simulation errors of all the experiments in the paper.



(a) (b)

Fig. 3 The tracks of ‘Chanchu’ (a) and ‘Prapiroon’ (b) in control and sensitivity runs and the best track



(a) (b)

Fig. 4 Variations of minimum sea level pressure sampled every 6 hours
(a) ‘Chanchu’ (b) ‘Prapiroon’

Table 3 Statistics of simulation errors

Test	Errors	Ctrl	Toba	Smith	SCOR	Liu
0601	RMSE of simulated pressure	11.8	9.0	8.5	8.7	8.6
	Correlation coefficient of simulated and observed pressure	0.818	0.900	0.907	0.906	0.906
0606	RMSE of simulated pressure	6.1	4.9	3.8	3.9	3.8
	Correlation coefficient of simulated and observed pressure	0.902	0.920	0.932	0.927	0.930

5. Conclusions

The ocean wave effect under high wind condition is studied by numerical simulation tests. The research of sea surface roughness parameterization schemes have been reviewed and the sensitivity of a regional atmosphere-ocean coupled model to sea surface roughness parameterizations is also discussed in this paper. The following preliminary conclusions can be drawn:

(1)Ocean waves influence the sea surface roughness. By considering the dependent relationship between sea surface roughness and wave age, the effect of ocean waves on air-sea interaction under high wind condition is significant and can not be ignored.

(2)The regional atmosphere-ocean coupled model shows good capability in simulating the typhoon process in the South China Sea. The simulated intensity of typhoon is weakened by air-sea interaction in the coupled model. Compared with uncoupled atmospheric model, it improves the simulation results of typhoon track and intensity.

(3)The regional atmosphere-ocean coupled model is sensitive to sea surface roughness parameterizations. In the numerical simulation tests of typhoon processes, sea surface roughness parameterizations have little influence on typhoon tracks but have remarkable influence on the typhoon intensities. The coupled model using the parameterizations of Smith (1992) and Liu (2007) gave better results in these tests. This study is helpful to make more reasonable parameterizations of the physical process of air-sea interaction and improve the regional atmosphere-ocean coupled models.

Acknowledgements

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